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FORCES AND MOMENTS ON A YAWED AIRFOIL

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FORCES AND MOMENTS ON A YAWED AIRFOIL*

By Sighard Hoerner

The author elaborates, within the rules and regulations of the 1938 Prize Competition of the Lilienthal Society for Aeronautical Research, the flow phenomena, forces and moments on airfoils in yaw. The existing experiments with straight wings (zero dihedral), wings with dihedral, and wings with sweepback are evaluated within the range of sound angles of attack, explained by calculations and generally enlarged.

SUMMARY

1. The total forces (c_a and c_w) are practically unaffected by yaw (up to $\tau \approx 25^\circ$). The newly appearing lateral force is derived for wings with and without dihedral.

2. The rolling moments due to yaw which exert a righting effect on straight airfoils (zero dihedral) in contradiction to the calculations made up to the present, are explained by a corner effect, an edge effect, and by the dissimilar yawed flow of the two wing-halves. The known wind-tunnel experiments are given in diagram form so that the rolling and yawing moments can be read from figures 5 and 6.

3. Dihedral produces subsidiary rolling and yawing moments due to yaw. The calculation of the rolling moment is confirmed by measurement.

4. The yawing moments due to sweepback were computed. Both yawing and rolling moments are confirmed by measurement.

5. Since the yawing moments due to yaw are often very small, considerably greater instrumental accuracy is required in order to achieve agreement between calculation and measurement.

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*"Kräfte und Momente schrägangeströmter Tragflügel." Luftfahrtforschung, vol. 16, no. 4, April 20, 1939, pp. 178-183.

INTRODUCTION

I. EFFECT OF YAWED FLOW ON TOTAL FORCES

The wing forces (total forces) are, in general, very little altered by yawed flow. Thus, at angles of yaw up to $\tau = 8^\circ$ the lift and drag of a rectangular wing is practically unaffected, according to the findings (reference 4). More than that, here - as in reference (13), figure 4 - the pitching moment is found to remain practically unchanged up to angles of yaw of $\tau \approx 35^\circ$.

According to reference 10, the lift c_a of large span wings decreases approximately as $\cos^2 \tau$, for constant angle of attack. In the above case the lift would be 2.5 percent lower at $\tau = 8^\circ$, according to this calculation. But on a rectangular wing the fact that the wing diagonal is turned transverse to the direction of flow, the span facing the wind is at first slightly increased. The reduction computed at $\cos^2 \tau$ is therefore so much less on rectangular wings as the chord is greater. For $\lambda = 1$ aspect ratio (circular disk), there is no further reduction in the span facing the wind. Only the angle of attack α is changed to the amount of $\sim \cos \tau$. Hence for wings with aspect ratios between 1 and around 5, the lift is proportional to $\cos \tau$ to $\cos^2 \tau$. Measurements affording further information regarding it are not known.

In yawed flow a subsidiary force occurs transverse to the wind direction. This force can be dealt with as a part of the induced drag, according to figure 1. It is $c_{si} = c_{wi} \sin \tau$. The force c_{si} is toward the side of the forward located wing tip, hence may be termed positive. In other words:

$$c_{si} = + \frac{c_a^2 \sin \tau}{\pi \lambda} \tag{1}$$

this lateral force is dependent on c_a^2 and on the aspect ratio.

Figure 1 compares measurements from reference 6 with the calculation. In Blenk's report (reference 4), the lateral force is in contrast to reference 6, measured in the direction of the lateral axis of the wing. With the aid of the concurrently measured drag forces, the measurements can be converted from one reference direction to the other. The agreement between the measurements and the calculation is satisfactory if the smallness of the involved forces is taken into account. Thus a value of $c_{si} = 0.01$, corresponding to the profile drag of a good wing, is only reached at around $\tau = 10^\circ$ and $c_a = 1.0$.

In span direction, only a component of the skin friction or profile drag can be applied. This lateral force

$$c_{sp} = - c_{wp} \sin \tau \tag{2}$$

therefore, is like the profile drag, approximately unaffected by c_a, its direction is toward the rearward-lying wing tip (negative).

The top portion of figure 1 shows the c_{sp} forces. The blunt sides of the rectangular wings of reference 4 give naturally higher c_{sp} values in yawed flow. The test values (reference 4) are, in consequence, about three times as high as the value $\dfrac{\partial c_{sp}}{\partial \tau^\circ} = 0.00026$ computed from $c_{wp} = 0.015$.

Sweepback induces no marked changes in figure 1; the test points from reference 4 confirm this. But dihedral causes an additional yawing lateral force (toward the backward lying wing tip). According to figure 2, $S_v = 2 \Delta A \varphi$ or $c_{sv} = \Delta c_a \varphi$. For Δc_a the subsequently derived amount $\tau \varphi \left(\dfrac{\partial c_a}{\partial \alpha}\right)$ is introduced.

$$c_{sv} = - \tau \varphi^2 \frac{\partial c_a}{\partial \alpha} \tag{3}$$

This lateral force acts toward the backward lying wing tip (negative).

Theory and measurements are compared in figure 2. In the calculation of the curve $\dfrac{\partial c_{sv}}{\partial \tau^\circ} = \dfrac{\pi^2}{180^2} \varphi^{\circ 2} \dfrac{\partial c_a}{\partial \alpha^\circ}$, a mean value $\dfrac{\partial \alpha}{\partial c_a} = 14^\circ$ was substituted for the experimental aspect ratios $\lambda = 5$ and 6. The measurements indicate about

82 percent of the theoretical values; the agreement is good (quadratic rise with dihedral). The independence of c_a is also confirmed (reference 6).

II. ROLLING MOMENTS DUE TO YAW~~ING~~ OF STRAIGHT WINGS

Blenk (reference 1) and Weinig (reference 2) attempted to compute the rolling moment in yawed flow on a straight wing (zero dihedral). Physically their calculation is to the effect that through the lift of the forward lying half according to figure 3, a certain upwind (reduced downwash) is induced at point 1 of the rear half of the wing. At point 2 on the forward half the flow is, on the other hand, more strongly deflected downward because the induction on the part of the rear half is small. From the corresponding distribution of the induced angle over the span of the wing follows a rolling moment which tends to turn the wing down toward the forward side 2. Fortunately, this aerodynamically undesirable rolling moment does not occur in reality. The wind-tunnel measurements discussed elsewhere indicate - contrary to the single statement in reference 3 - agreeable positive rolling moments due to yaw, whereby the aerodynamically desired righting sense of rotation is counted positive.

In the range of sound angles of attack (up to $\alpha \approx 15^\circ$), the rolling moment measurements (references 4 to 7) indicate an increase over the lift coefficient (or angle of attack) which, for practical purposes, at least, may be dealt with as a straight line; hence the rise $\partial c_L/\partial c_a$ in figure 4. Up to about 25° angle of yaw the measurements likewise indicate a practically linear distribution over the angle of yaw; hence the subsequent plotting of $\frac{\partial c_L}{\partial \tau} \frac{1}{\partial c_a}$ according to figure 5 is justified.

The rolling moment due to yaw~~ing~~ about a circular wing (aspect ratio $\lambda = 1$) can be mathematically defined. The angle of attack of the circular disk of figure 4 would become zero at $\tau = 90^\circ$. For practical purposes the definition of constant c_a in yawed flight is more fitting. Therefore the circular disk is to be so turned as to present a constant angle of attack to the direction of flow at all angles of yaw. In accord with this definition, the lift is always applied at the median axis of the circular disk and the rolling moment due to yawing referred to the wind axis x becomes zero while, referred to the x' axis, it gives a positive moment value. According to figure 4, the lift is applied at near t/3 (Jour. of the Aero. Sciences, vol. 4, 1937, p. 499) from the momentary forward point of the wing. Accordingly, the rolling moment referred to the x' axis is $L = A \times 0.2\ t \sin \tau$, its coefficient $c_L = \frac{L}{qF} \times 0.5\ b = 0.4\ c_a \sin \tau$ and the derivation

$$\frac{\partial c_L}{\partial c_a} = 0.4 \sin \tau \qquad (4)$$

circular disk?

plotted in figure 4. This rolling moment is positive, i.e., righting. For $\tau = 90°$, the rolling moment can equally be computed for other aspect ratios. If referred to wind axis x, it again yields zero; if to wing axis x, it is equal to the longitudinal moment of a wing of reciprocal aspect ratio $1/\lambda$ at $\tau = 0°$. The point of application of the air force is again assumed at 0.3 of the span b, and the result is as for the circular wing, $c_L = 0.4\ c_a$; $\partial c_L/\partial c_a = 0.4$. With the exception of the circular wing, the calculation at other angles of yaw is not very easy. But the obtained points in figure 4 are very useful for purposes of extrapolation. The steep ascent of the curves at $\tau = 60°$ to $70°$ indicates that here the rear wing half rises, so to say, from out of the tip vortex up current of the forward half and into its downwash zone.

The rectangular wings manifest throughout substantially greater rolling moments due to yaw~~ing~~ than the rounded wings. Figure 3 explains this as follows: the wing span on the forward tip is increased by the rear corner 3. At the rear tips the forward profile portions lose the rear portions 4 necessary to produce the circulation. This corner effect is particularly noticeable on wings of small aspect ratios. Hence the curve for $\lambda = 1$ obtained from the circular wing calculation is exceeded by about 60 percent on the measured rectangular wings (fig. 4); at $\lambda = \infty$ the corner effect is proportionally zero. Consequently, the extrapolation of the two curves in figure 5 to $1/\lambda = 0$ yields one and the same point.

This corner effect is not solely responsible for the positive sign of the rolling moments due to yaw, as proved on a wing, the sides of which had been beveled in the direction of a 20° angle of sideslip. The values of the wind-

Wrong because C_m cannot be zero about both systems of axes.
Taft 2/28/41

tunnel measurements plotted in figure 4 are mostly referred to wind axis x. They can be reduced approximately to the x' axis; it is $c_{Lf} = c_{Lw}/\cos\tau$, wherein f = wing axis, w = wind axis. Up to about 20° angle of yaw, the difference of the two reference types is, according to figure 4, secondary for the recorded aspect ratios of $\lambda \geqq 5$. For $\lambda = 1$, this conversion is no longer applicable - not even approximately.

Figure 5 shows the values $\frac{\partial c_L}{\partial c_a}\frac{1}{\delta\tau}$ of figure 4 for small angles of yaw $(\tau \leqq 25°)$ plotted against aspect ratio. The experiments made at $\lambda = 5$ and 6 manifest substantially smaller rolling moments than computed for the circular wing. This evidently is the effect referred to by Blenk and Weinig, according to which a negative rolling moment is to be expected in yaw as a result of the local angle of attack distribution. For $\lambda \geqq \sim 20$, the rolling moments actually are negative to the extent that the effected extrapolation may be adduced as proof.

In yaw the lift distribution is perceptibly shifted toward the forward wing tip. From the pressure distribution measurements of reference 7, at $\tau = 20°$, the lift is symmetrically distributed over the span at $c_a = 0.1$. At $c_a = 0.3$, there is a lift concentration on the forward tip of the wing, and a lift decrease on the rear tip. At $c_a = 1$, the edge of the forward tip discloses a distinct lift concentration caused by flow around the edge. (See point 5, fig. 3.) Hence the forward tip is subjected to a flow around its leading edge as well as its sides. The form of the wing tip and of the lateral edge therefore, has, quite comprehensibly, a noticeable effect on the size of the rolling moments due to yawing. Logically, this edge effect is more pronounced at small aspect ratios; the effect is proportionally so much less as the span is greater.

A further reason for the existence of the positive rolling moments may finally be found in the deformation of flow in angle-of-attack direction as well as laterally. According to figure 3, the flow is deflected from the forward half 6 toward both sides. As a result of it the flow on the wing profiles of the forward half is a little less; on the rear half, a little more yawed, 7. Correspondingly, the lift on the forward wing is increased; on the rear, reduced. The rolling moment due to yawing therefore stems from several sources: from the mathematically known induction effect, the corner effect associated with the plan of the wing, the flow around the edge associated with the aspect ratio, and the lateral dissimilarity of the yawed flow. Lastly, the dissimilar formation of the boundary layer itself may cause a change in rolling moment. Only the induced amount is negative. The other positive ones are preponderate at aspect ratios up to $\lambda \approx 20$.

III. YAWING MOMENT DUE TO YAW~~ING~~ OF STRAIGHT WINGS (ZERO DIHEDRAL)

The rolling moment is the result of a difference in lift between the left and right halves of the wing. As the locally induced drag changes with the local lift, a yawing moment is always causatively associated with a rolling moment. In the present report, the righting moment from an angle of yaw, in the sense of the fin of an airplane, is dealt with as positive yawing moment due to yaw.

For magnitude and aspect of a yawing moment, the reference system is essential. While in a wind system of axes the drag forces produce the yawing moment exclusively, in a body system of axes the tangential lift component is also a heavy contributor. Reference 3 is, in this respect, the only source citing positive yawing moments. All other known wind-tunnel measurements are reported in a wind system of axes. A change in angle of yaw is followed by a change in rolling moment through shifting of the lift or change in lift distribution. In this case (c_a constant) the yawing and the rolling moment change (in the zone of medium angles of yaw; $\tau \leq 25^{\circ}$) proportional to the angle of yaw.

The yawing moment for the circular wing is also readily computable. It is zero for all c_a values if the reference axis passes through the center of the wing plan, i.e., $t/2$; for under the foregoing assumption (constant c_a) the air force is always applied symmetrically - i.e., passing through the center of the circle. Placing the reference axis through $t/4$ as frequently practiced in wind-tunnel tests, yields a positive yawing moment, conformable to figure 6. With the lever arm $0.25 \sin \tau$, it affords $c_N = \frac{N}{qF} 0.5\ b = 0.5\ c_w \sin \tau$. Introducing only the induced value $c_a^2/\pi\lambda$ for c_w for reasons of mathematical simplicity, leaves for $\lambda = 1$

$$c_{N_1} = \frac{0.5\ c_a^2\ \sin\tau}{\pi} \tag{5}$$

For other aspect ratios the yawing moment due to yaw (at constant τ) also has the tendency to increase with c_a^2, being the result of the change of local induced drag associated with the local c_a. Departures from this quadratic course occur, among others, through the influence of the profile drag. Thus the yawing moment due to yaw at $c_a = 0$ has a small positive value according to various experiments. According to reference 5, for instance, it is in this case $\frac{\partial c_N}{\partial \tau^0} \approx 0.0001$. By comparison, the righting yawing moment produced with a conventional lateral control system at 10° yaw, amounts to $c_{N_s} \approx 0.7$ and $\partial c_{N_s}/\partial \tau^0 \approx 0.7$. According to that, the above amount induced by the profile drag can be disregarded.

The values $\frac{\partial c_N}{\partial \tau} \frac{1}{\partial c_a^2}$ obtained from the data of references 4 to 6 are shown in figure 6. The passing of the plotted curve through the horizontal axis conforms to that of figure 5. If the rolling moment is zero the yawing moment must be zero also, disregarding the slight profile drag portion.

Since practically all experiments are referred to the wind-fixed normal axis passing at 0.25 t of the median wing axis, a point computed according to equation (5) may be plotted for $\lambda = 1$. Two test points of reference 5 are in little agreement with this computed point. Additional experiments at small aspect ratios will have to decide whether the calculation or the cited test points are preferable. This question is not critical, however, since the yawing moments of the wings are in general very small, being of the order of magnitude of 1 percent of the previously quoted amount of the lateral control system.

IV. YAWING MOMENTS DUE TO DIHEDRAL ANGLE

The calculation of the rolling moments due to yaw caused by the dihedral is known (references 8 and 9). In yaw the angle of attack ~~dihedral~~ of a given wing is geometrically increased for the forward half of the wing and decreased for the rear half, by an amount $\Delta\alpha = \tau\varphi$ (φ = angle of dihedral). To $\Delta\alpha$ corresponds

$$\Delta c_a = \pm \tau \varphi \frac{\partial c_a}{\partial \alpha} \tag{6}$$

with $b/4$ as lever arm of the amounts of Δc_a. Then the rolling moment follows at

$$c_L = \frac{L}{qF\ 0.5b} = \frac{\Delta c_a}{2} \tag{7}$$

and the rolling moment due to yaw~~ing~~ caused by the dihedral angle at

$$c_{Lv} = \frac{\tau\varphi}{2} \frac{\partial c_a}{\partial \alpha} \tag{8}$$

the angles being expressed in radians.

The available measurements (references 4 and 5) confirm the fact following from the derivation that the rolling moment due to yaw~~ing~~ caused by dihedral is not related to c_a.

In figure 7 the differences in rolling moment c_{Lv} or their increase $\partial c_{Lv}/\partial\tau$ due to dihedral are shown plotted against the dihedral angle. The theoretical curve was obtained with a mean value of $\partial\alpha^o/\partial c_a = 14^o$ applicable to the experimental aspect ratios $\lambda = 5$ and 6. The measured values reach only about 70 percent of the curve values - due in part to the fact that in the calculation for $\partial\alpha/\partial c_a$, the value of the wing in rectilinear flow had been used. Considering as opposite extreme, the wing halves flying separately and at half as great an aspect ratio, the computed curve in figure 7 is reduced by 19 percent. That the lever arm with $b/4$ was too great is not likely, because edge and corner effect act on great lever arms. The remaining difference between calculation and experiment is therefore again due to the mutual induction of the two half-wings disregarded in the calculation.

A yawing moment is causatively associated with the rolling moment through the change in induced drag. The side of the wing pushed upward under the effect of a positive rolling moment will, through its greater induced drag, have a tendency to stay behind.

The supplementary rolling moment due to yawing caused by the dihedral can be computed, according to Diehl (reference 9). It is on each half-wing

$$c_{wi} = \frac{(c_a \pm \Delta c_a)}{\pi \lambda} = \frac{c_a^2 \pm 2 c_a \Delta c_a + (\Delta c_a)^2}{\pi \lambda} \tag{9}$$

Subtraction gives the drag difference between one and the other half at

$$\Delta c_{wi} = \frac{2 c_a \Delta c_a}{\pi \lambda} \tag{10}$$

With a lever arm assumed at $b/4$ the yawing moment is

$$c_N = \frac{N}{qF\ 0.5\ b} = \frac{\Delta c_w}{2} \tag{11}$$

Hence the yawing moment due to yawing caused by the dihedral follows from (10) and (11) at

$$c_{Nv} = \frac{c_a\ \tau\ \varphi}{\pi \lambda} \frac{\partial c_a}{\partial \alpha} \tag{12}$$

This yawing moment is, accordingly, proportional to c_a; it is intimately related to the aspect ratio, according to figure 8. Unfortunately, the obtainable measurements fail to confirm this moment qualitatively or according to prefix. The sources (references 4 and 6) both indicate - contrary to concept - a slight reduction of the yawing moment due to yaw as a result of the dihedral. Again the smallness of the moments will be observed. They range in the same order of magnitude as the yawing moments due to yaw of straight wings. Additional experiments are necessary.

V. YAWING MOMENT DUE TO SWEEPBACK

at same α

As stated in the beginning of this report, the lift of a straight wing in yaw is approximately proportional to $\cos^2 \tau$. Visualizing, as in Betz's article (reference 10), the two halves of a sweptback wing in yaw, as flying independently of each other, their lift amounts to $c_a \cos^2(\tau \mp \gamma) = c_a (\cos \tau \cos \gamma \pm \sin \tau \sin \gamma)^2$, γ being the angle of sweepback. Subtraction then gives the lift difference between the two halves at

$$\Delta c_a = 2 c_a \cos \tau \cos \gamma \sin \tau \sin \gamma = c_a \frac{\sin 2\tau \sin 2\gamma}{2} \tag{13}$$

From equations (7) and (13) the additional rolling moment due to yaw~~ing~~ caused by the sweepback follows at

$$c_{Lp} = c_a \frac{\sin 2\tau \sin 2\gamma}{4} \approx c_a \tau \gamma \tag{14}$$

This rolling moment due to yaw~~ing~~ is dependent upon c_a, but independent of the aspect ratio. The measured values amount to about 70 percent of the computed curve, according to figure 9. Evidently the mutual interference of the two halves is here also superimposed on the simple calculation.

The yawing moment due to yawing of a wing with sweepback is the result of the change of the induced and of the profile drag of the two halves. The difference of the induced drag of one half from the other follows from equation (10) as for the dihedral. This (equation 10) in conjunction with (11) and (13) gives the induced yawing moment of a wing with sweepback at

$$c_{Npi} = \frac{c_a^2 \tan \tau \tan \gamma}{\pi \lambda} \tag{15}$$

This moment therefore changes with c_a^2; it is, in addition, dependent upon the aspect ratio.

For the profile drag of a straight wing in yaw, the simple assumption is made that its change is proportional to the span facing the wind: i.e., $c_{wp} \sim \cos \tau$. The profile drag of each half of a wing with sweepback changes accordingly. For the forward half it amounts to c_{wp} cos $(\tau - \gamma)$, for the rear half $c_{wp} \cos (\tau + \gamma)$, giving a difference after subtraction, of $\Delta c_{wp} = 2c_{wp} \sin \tau \sin \gamma$. With equation (7) the yawing moment due to yaw of a wing with sweepback caused by profile drag becomes:

$$c_{N_{pp}} = c_{wp} \sin \tau \sin \gamma \tag{16}$$

The yawing moments due to yawing of Blenk's wing with sweepback (reference 4) are plotted in figure 10 and compared with the calculation for $c_{wp} = 0.02$ and $\gamma = 5$. The widely scattered test points lie, on an average, above this computed curve.

In the prediction of the induced yawing moment the aspect ratio enters direct; without being previously examined, it was put equal to the total wing. With about the same justification, the aspect ratio of the half-wing supposedly flying free without mutual induction ($\lambda = 2.5$) may be introduced. The thus-computed c_{N_p} values lie in part above the test points as expected, similarly to the rolling moments due to yawing of figure 9. Again the smallness of the yawing moments and the ensuing inferior instrumental accuracy is to be noted.

Translation by J. Vanier,
National Advisory Committee
for Aeronautics.

Equations Derived for the Prediction of Forces and Moments in Yaw

Force or moment	Approximate calculation	Experimental proof
Lateral force transverse to wind	C_l $c_{si} = + \frac{c_a^2 \sin \cancel{\tau}\, \psi'}{\pi \lambda}$	~ 100 percent
Lateral force spanwise	C_y $c_{sp} = - c_{wp} \sin \tau$	~ 100 percent
Lateral force due to dihedral	C_Y $c_{sv} = - \tau \varphi^2 \frac{\partial c_a}{\partial \alpha}$	80 percent
Rolling moment due to dihedral	$\psi\ \gamma$ $c_{Lv} = + \frac{\tau \varphi}{2} \frac{\partial c_a}{\partial \alpha}$	70 percent
Yawing moment due to dihedral	$c_{Nv} = \overset{-}{+} \frac{c_a \tau \varphi}{\pi \lambda} \frac{\partial c_a}{\partial \alpha}$	Not confirmed
Rolling moment due to sweepback	$c_{Lp} = + c_a \frac{\sin 2\tau \sin 2\gamma}{4} \approx$ $\approx c_a \tau \gamma$	70 per cent
Yawing moment due to sweepback	$c_{Npi} = + \frac{c_a^2 \tau \gamma}{\pi \lambda}$	~ 70 percent
Yawing moment due to sweepback	$c_{Npp} = + c_{wp} \tau \gamma$	~ 80 percent

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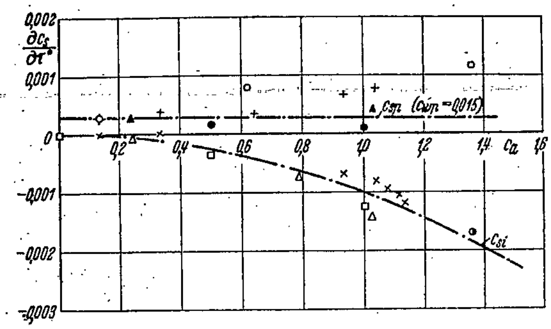
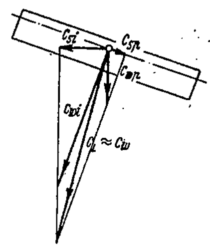


Luftf. Forschg. 1929 S.27
$\lambda = 5$; Sharp edges.
o Wing axis measurement
⊙ Computed from c_{sp} and c_w
N.A.C.A. Rep. 548; $\lambda = 6$
□ Wind axis measurement
● Computed from c_{si} and c_w
N.A.C.A. Rep. 431 (Sharp rectangular wing)
× Wind axis measurement; $\lambda = 6$
+ Computed from c_{si} and c_w
△ Wind axis measurement; $\lambda = 3$
▲ Computed from c_{si} and c_w

Figure 1.- Lateral forces on a yawed wing.



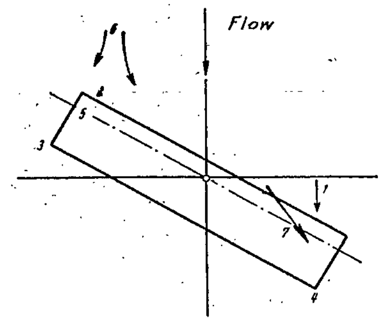


Figure 3.- Circulation about straight wing in yaw.

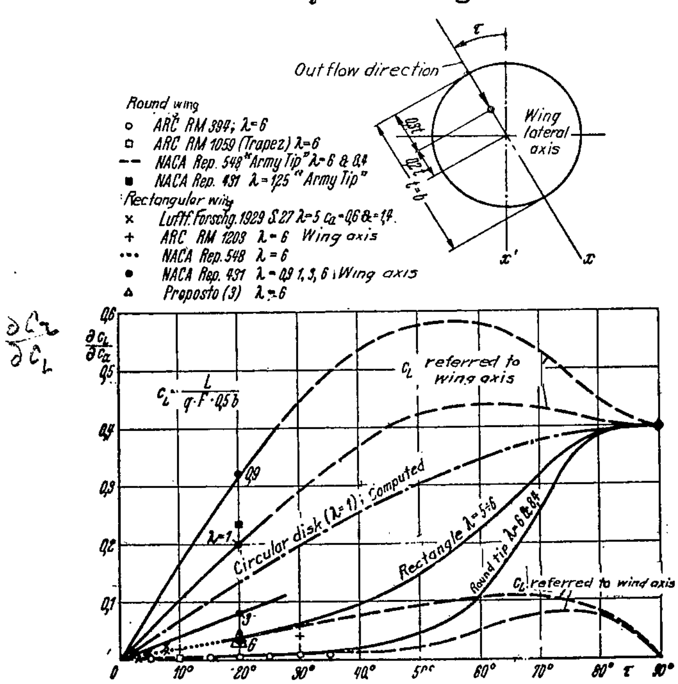


Figure 4.- Rolling moments due to yawing of straight wings (zero dihedral).

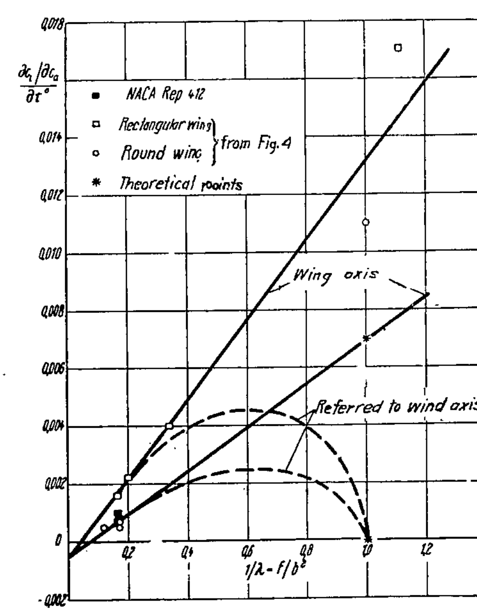


Figure 5.- Rolling moments due to yawing against aspect ratio; applicable to $\tau \approx 0$ to $25°$.

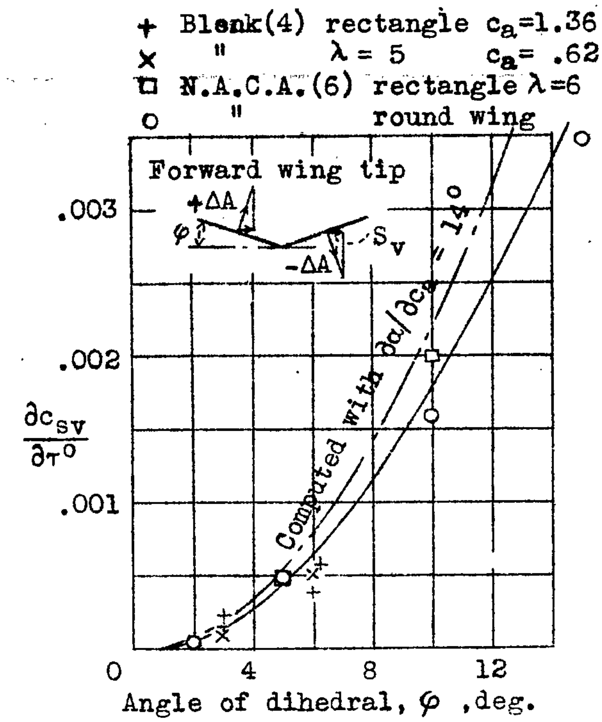


Figure 2.- Supplementary lateral force due to dihedral.

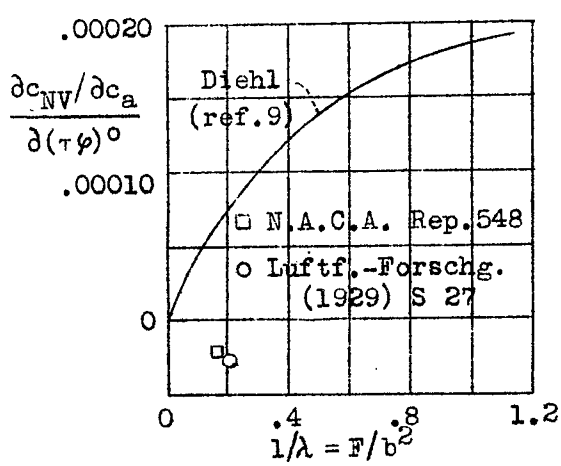


Figure 8.- Additional yawing-rolling moments caused by dihedral.

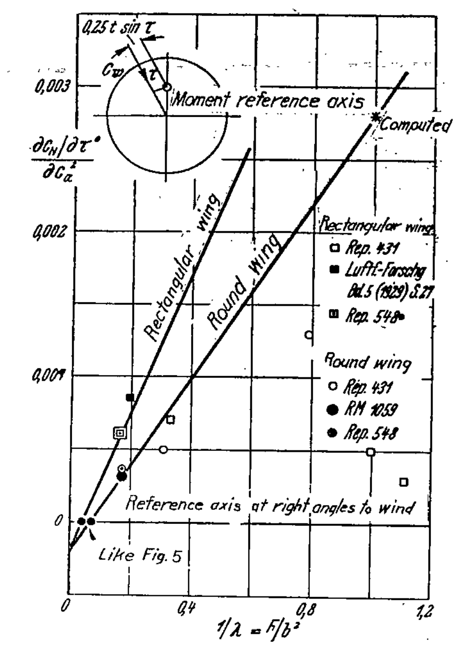
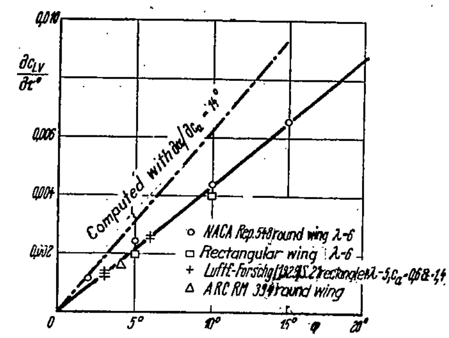
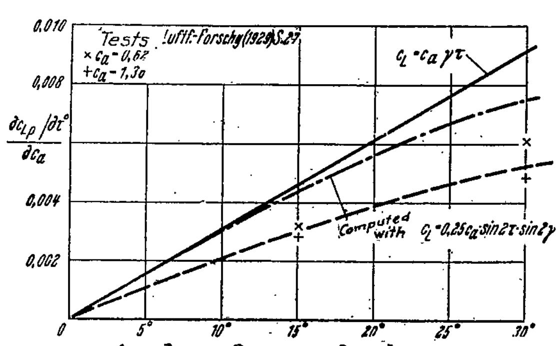


Figure 6.- Yawing moments due to yawing of straight wings (zero dihedral).



Angle of dihedral, V

Figure 7.- Rolling moments due to yawing caused by dihedral.



Angle of sweepback, γ

Figure 9.- Rolling moments due to yawing caused by sweepback.

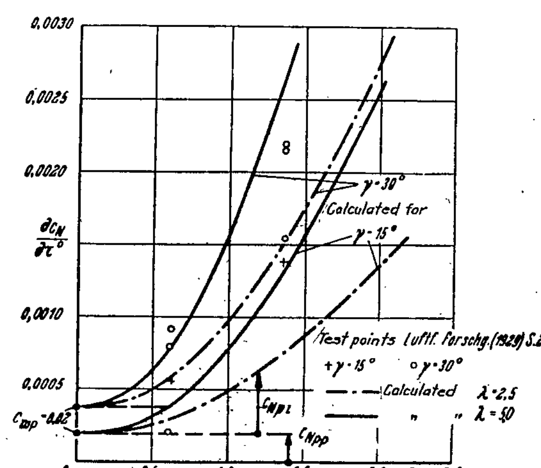


Figure 10.- Yawing moments due to yawing caused by sweepback